A DESIGN OF A CAPACITANCE TYPE INSTRUMENT FOR THE DETECTION OF THE LEVEL OF CONDENSED FREON-12 IN A HORIZONTAL LINE

by

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INTRODUCTION

The design of an electrical capacitance type liquid level instrument was initiated because an accurate method of measuring the level of condensed Freon-12 entering and leaving a horizontal tube was required in a research project at Kansas State College. The present method of measuring level makes use of sight glasses and visual measurements. Accurate measurement was hindered by distortion of the glass and the constant disturbance of the liquid partially due to the uninsulated sight glass causing condensation within the sight glass itself.

This thesis covers a review of literature on capacitance type liquid level instruments, design and calibration of an instrument, and research on the dielectric properties of Freon-12 which may be useful in a future design.

THEORY OF OPERATION

The theory of operation can probably be more easily understood after a brief outline of the electrical characteristics of capacitors.

An ideal capacitor, connected to a sinusoidal voltage source of

$$v = v_o e^{j \quad t}$$

where   is the angular frequency, stores, when vacuum is its dielectric, a charge of

$$Q_o = C_o v$$

and draws a charging current of

$$I_c = \frac{dQ}{dt}$$

which leads the voltage by an angle of 90^o.

When filled with a dielectric substance the capacitor increases its capacitance to

$$C = C_o \frac{D'}{D_o}$$

where D' and D_o are the dielectric constants of the dielectric and vacuum respectively and their ratio is the relative dielectric constant. Hereafter in this thesis, this will be referred to only as dielectric constant.

If a liquid has a dielectric constant of two, a capacitor filled with the liquid will have about double the capacity it had with air or vacuum as the dielectric. If it is of the proper physical shape, the amount of liquid could be determined by measurement of its electrical capacity and the element could be thought of as a capacitance type transducer. The transducer, together with a capacitance measuring device calibrated in liquid level, would make up a capacitance type liquid level indicator.

REVIEW OF LITERATURE ON CAPACITANCE INSTRUMENTS

The advantages of capacitance elements for use in liquid level indicators are, (a) they may be very simple and rugged, (b) there are no moving parts, (c) they may be shaped to give various characteristics, and (d) they may be used in groups to give average indications or to sum the level in several tanks.

The disadvantages are that the liquid must have consistent dielectric properties and be as free as possible from contaminants which might alter the dielectric constant or form deposits on the elements.

Most military aircraft today use capacitance type fuel gauges. Since aircraft fuels have the property of a decrease in dielectric constant with an increase in specific volume, the elements may be designed to give a fairly accurate indication of the fuel quantity in pounds. Since the energy content is determined by the mass rather than the volume, the pound indication is much more reliable when estimating the available flight time.

An article by Clark and Adolphe (3) explains six different types of capacitance fuel gauges which were submitted to Lockheed Aircraft for test in 1947. A schematic of the simplest type is shown in Plate I. This basic circuit is used by several manufacturers today.

The Technical News Bulletin of the National Bureau of Standards (14) discusses the application of this type instrument as a liquid level indicator for condensed hydrogen and nitrogen gases at the NBC-AEC Cryogenic Laboratory at Boulder, Colorado. The materials used in the element had to maintain their structural characteristics to near absolute zero.

Hawkins (11) describes a U-tube manometer using metal tubes coated with a dielectric. The mercury acts as a variable inner conductor and the two sides of the tube are connected to a capacitance bridge circuit.

EXPLANATION OF PLATE I

Schematic diagram of fuel gauge circuit

E = Voltage

I = Current

A = Amplifier

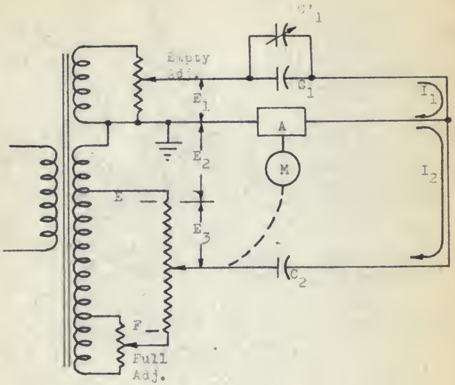
M = Motor to drive balancing pot

C_1 = Empty tank capacitance

C_1' = Added capacitance due to fuel

C_2 = Fixed reference capacitor

PLATE I



1. Condition for balance at empty ($C'_1 = 0$)

$$I_1 = I_2$$

Empty adjustment made so that $E_1 C_1 = E_2 C_2$

2. Condition for balance with fuel in tank ($C'_1 \neq 0$)

$$I_1 = I_2$$

$$E_1 C_1 + E_1 C'_1 = E_2 C_2 + E_3 C_2$$

But by Empty Adjustment:

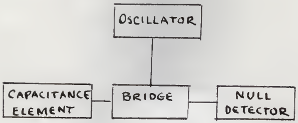
$$E_1 C_1 = E_2 C_2$$

So: $E_1 C'_1 = E_3 C_2$

Then: $E_3 = \dfrac{E_1 C'_1}{C_2}$

DESIGN OF THE INSTRUMENT

The basic instrument configuration is shown below.



The capacitance element acts as one leg of a wheatstone bridge circuit. As the liquid level changes the capacitance changes, thus unbalancing the bridge circuit which is supplied by the oscillator. The bridge is then manually balanced until a null is indicated by the detector. The position of the balancing element gives an indication of the level.

The finished units of the instrument are shown in Plate II with the exception of the oscillator which may be any conventional audio oscillator or 1000 cps bridge oscillator with fairly good waveform.

Explanation of the design of each component is given below.

The Capacitance Element

The element used in this instrument was to have a half inch inside diameter, was to be as short as possible, and was to present as little restriction to flow as feasible. It consists of two concentric tubes. The outer tube is a brass pipe with standard plumbing fittings on both ends. The inner is a very thin brass tube supported at three points on each end by thin Teflon spacers as shown in Plate III.

EXPLANATION OF PLATE II

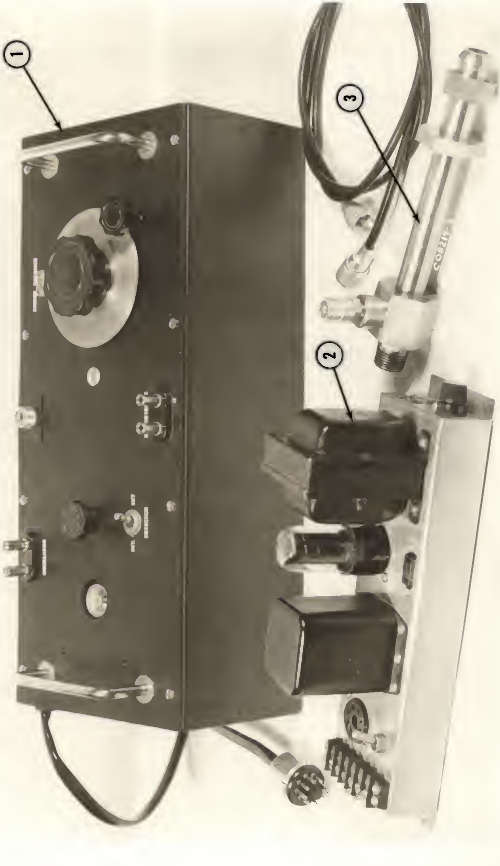
The liquid level instrument consisting of

1. The bridge and detector unit

2. The power supply

3. The capacitance element

PLATE II



EXPLANATION OF PLATE III

End view of the capacitance element showing the inside electrode, the teflon spacers, and the electrical connection

PLATE III

The silhouette appears to be larger than actual size because the spacers do not quite coincide on each end.

Details of the pressure tight electrical connector to the inner tube are shown in Plate XVIII in the appendix. Teflon plastic was chosen as the insulating material on the basis of a brief discussion in the DuPont Bulletin (6) on the effect of the Freon compounds on plastics. Teflon is used extensively as an insulation in military equipment and high frequency applications because of its efficiency at high and low temperatures, its extremely low loss, and its high voltage breakdown.

The physical and electrical properties of Teflon are well outlined in a publication by the Amphenol Electronics Corporation (4).

According to Smith (21) the formula for calculating the capacity between concentric cylinders is

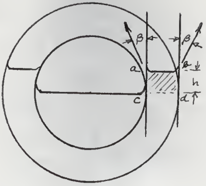
$$C = \frac{7.354\,D}{\log_{10} \frac{d_o}{d_i}}$$

d_o = inside diameter of outer cylinder (inches)
d_i = outside diameter of inner cylinder (inches)
D = dielectric const. of material in the gap.

This formula neglects the fringing effect at the end of the cylinders. Since the capacitance increases as the ratio of $\frac{d_i}{d_o}$ increases, it was desirable from the standpoint of sensitivity to make the inner cylinder as large as possible. The size was limited, however, by the capillary effect of the liquid between the plates.

The capillary effect was calculated at the point where the liquid level is half the pipe diameter by considering this point approximately

equivalent to two parallel plates. The equations were derived as shown below.



Neglecting the fluid weight above the low point of the meniscus the weight of the fluid is given by

$W = \rho h l x$ 　　 ρ = density
h = capillary rise
x = distance between plates

The vertical force upward which sustains this weight is given by

$F = 2\sigma \cos\beta\, L$ 　　 σ = surface tension
β = contact angle of fluid
L = length of plate

Combining the two equations gives

$$hx = 2\sigma\cos\beta$$

Since Freon-12 exhibits a film type condensation according to Hwang (13), the contact angle, β, was assumed to be zero. The equation then reduces to

$$h = \frac{2\sigma}{\rho x}$$

The DuPont Freon Technical Bulletin (6) lists the surface tension of Freon-12 at 77° F as .00061 $\frac{\text{lb.}}{\text{ft.}}$ and Gunther (9) gives the density

at 77° F as $81.83 \frac{\text{lb.}}{\text{ft.}^3}$

Then

$$h = \frac{.00122}{81.83x} \text{ feet}$$

If x is chosen as .1 inch

$$h = .00178 \text{ ft. or } .021 \text{ inches}$$

This was judged to be an acceptable capillary rise since the element was to be calibrated experimentally and would not be considered as accurate in the near full or near empty range.

Since the inside diameter of the outer tube was fixed at .500 inches this made the inner tube diameter .300 inches.

The capacitance of the element with air as the dielectric is

$$C = \frac{7.354}{\log_{10} \frac{.5}{.3}} = 33.4 \text{ mmf per foot (neglecting fringe effects)}$$

For an element capacity of about 16 mmf the length was found to be 5.75 inches. The measured capacitance was 16.6 mmf or about .6 mmf was due to fringe effects and the lead to the cable connector.

The element was then checked for sensitivity to temperature changes due to linear expansion of the brass.

Using the coefficient of the linear expansion for brass of .0000107, and a temperature range of 132° F., which would cover the saturation pressure range of Freon-12 from about 24 psia to 200 psia, the change of the inside tube diameter (d_i) would be

$$\Delta d_i = .0000107\, d_i \Delta T \qquad d_i = .300 \text{ inches}$$

$$\Delta T = 132^\circ \text{ F}$$

$$\Delta d_i = .00042 \text{ inches}$$

The change of diameter of the outer tube would be approximately

$\Delta d_o = .0000107\ d_o'\Delta T$ $\quad$ d_o' = average diameter of the outer tube (.625 in.)

$\Delta d_o = .000887$

The change in capacity is dependent on the change in the ratio of the tube diameters which would be

$$\frac{d_i + \Delta d_i}{d_o + \Delta d_o} - \frac{d_i}{d_o} = .0002$$

This value is negligible for the accuracy expected of this instrument as would be the change due to an increase in length.

$C = .000107\ C_o$ $\quad$ $C_o = 16$ mmf.

$C = .0017$ mmf.

The final check of the element dimensions consisted of a check of the pressure drop using the maximum liquid Freon flow rate and vapor flow rate obtained by Sun (24) in the Freon research project at Kansas State College.

The equation for pressure drop across the element is, according to Shapiro (19)

$$-\Delta P = \frac{4\ f \rho V^2}{2g\ D}$$

ρ = density
V = velocity
f = coefficient of friction
D = hydraulic Diameter

The hydraulic diameter is defined as four times the ratio of the cross sectional area to the wetted perimeter or

$$D = \frac{d_o^2 - .016\ d_i + .000064}{d_o + 2d_i - .008}$$

d_o = inside diameter of outer tube (.500 in.)

For dimensions of the element

$D = .227$ inches or $.018$ feet

d_i = outside diameter of inner tube (.300)

Wall thickness of inner tube is .004 inches

For a liquid flow rate of 164 lb/hr. and an average temperature of 130° F we get a Reynolds number of 9000. From the pipe friction coefficient charts in Mark's Mechanical Engineering Handbook, the friction coefficient was found to be .032. The viscosity according to McAdams (15) is .000154 $\frac{\text{lb.}}{\text{sec ft}}$. The velocity is .46 ft/sec.

Solving the pressure drop equation we have

$$-\Delta P = \frac{4\ f \rho V^2}{2\ g\ D} = 1.64 \text{ psf/ft length}$$

or the element pressure drop is

$$-\Delta P_e = .0057 \text{ psi}$$

A similar procedure using a vapor flow rate of 194.9 lb/sec gives a pressure drop of

$$-\Delta P_e = .061 \text{ psi}$$

Sun (24) has measured pressure drops in the test section of the Freon experiment up to .2345 psia.

It will be necessary for those doing the Freon research to analyze the effect of the element on their particular set of conditions in order to determine its suitability for the application.

The Bridge

Assuming an average dielectric constant of two for the liquid Freon, the change in element capacity from empty to full would be about 16 mmf. When a cable is connected to the element the total capacity is then the sum of the element and cable capacity. The sensitivity of the bridge to changes in level would be dependent to some extent on the ratio of the change in capacity to the total capacity. The cable was

made from Amphenol type RG59/u which has a capacity of about 21 mmf per foot.

For a cable length of six feet the total capacity would be about 160 mmf. The reactance to a 60 cps signal would then be about 16 megohms which ruled out the use of the power line as a signal source.

1000 cps was chosen as the signal frequency and brings the reactance of 160 mmf down to .995 megohms.

Since the circuit shown in Plate I takes a special well balanced transformer, the standard wheatstone bridge circuit shown in Plate IV was chosen. The dotted lines indicate the electrostatic shielding which is necessary to fix the stray capacitance between the circuit elements and between the elements and ground.

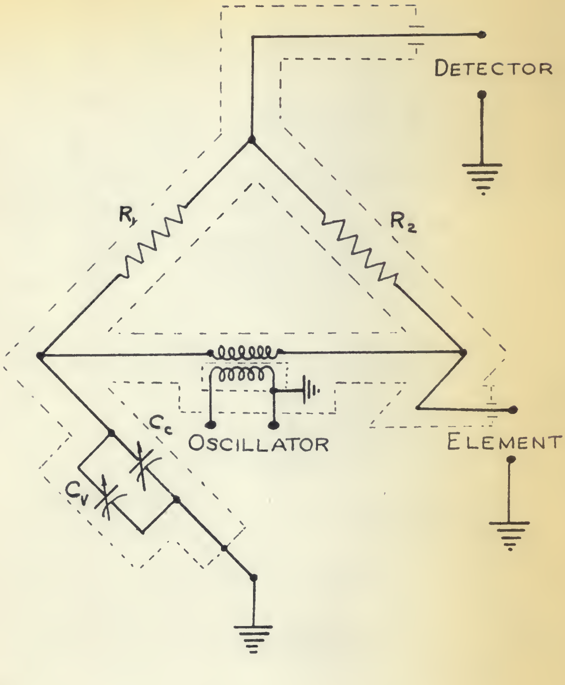
The ground electrode at the capacitance element is the outer tube which is connected to the bridge by the outer braided shield of the cable. Thus the element is completely shielded from stray capacitance. A Langevin type 400D input transformer with an electrostatic shield between the windings was used to isolate the signal input from the circuit. The capacitance of the secondary winding was then fixed with respect to ground, and the capacitance associated with the oscillator and connecting cables had little effect on the bridge. The Langevin 400D transformer has a turns ratio of 10:1 which presents a fairly high impedance signal source to the bridge.

Values of the two fixed resistances were chosen to be 11000 ohms since two precision 1% IRC resistors were available. The detector was to be electronic so its impedance was assumed to be infinite for purposes of checking the sensitivity to be expected from the circuit. Two

EXPLANATION OF PLATE IV

Schematic drawing of the basic bridge circuit. The dotted lines represent the electrostatic shielding of the components

PLATE IV



variable air dielectric capacitors were used as the balancing elements. One capacitor, a Hammarlund Type APC-140, has a range up to 140 mmf and was used as the cable balancing capacitor. The other, a Hammarlund type APC 50 had four moveable and three fixed plates removed so its capacity was variable up to about 25 mmf. This is the variable capacitance which is indicated as C_v in Plate IV and is used as the bridge balancing element.

If the bridge can be rebalanced for a change of .1 mmf of the capacitance element it would be capable of detecting a deviation of liquid level of about .6% of the span of the instrument. Assuming an unbalance of .1 mmf from a mean value of 160 mmf, a 1000 cps signal across the bridge of 10 volts would produce a signal at the detector of .00157 volts according to the equation below.

$$V_d = \frac{Z_1R_2 - Z_2R_1}{(Z_1+Z_2)(R_1+R_2)} \; V_s$$

$$V_d = \frac{Z_1 - Z_2}{(Z_1 + Z_2)2} = .00157 \text{ volts}$$

V_s = signal voltage

V_d = voltage at detector

$R_1 = R_2$ = bridge resistance arms

C = 160 mmf

f = 1000 cps

$$Z_1 = \frac{10^{12}}{j2\ \ fC}$$

$$Z_2 = \frac{10^{12}}{j2\ \ f\ (C + .1)}$$

This voltage may be easily detected with an electronic detector, and therefore the bridge has a sensitivity of 0.1 mmf or better.

Plates V, VI, and VII show the construction of the bridge and detector. Plate V shows the copper box which covers the variable capacitors and one of the reference resistors. The other reference resistor is between the chassis and front panel. Plate VI shows the bridge with the outer box removed. Note the copper shield which is placed between

the reference resistor and the large variable capacitor. Thus, each element is adequately shielded from the other elements. The larger variable capacitor is the cable adjusting capacitor and is adjusted with a screwdriver from the front of the instrument. The small capacitor is the bridge balancing element. Both capacitors have "Isolantite" bases which have very low current leakage. The reference resistors are mounted on porcelain standoff insulators for the same reason. Adequate spacing has been allowed to keep the values of stray capacitance as low as possible. The front panel is masonite so the inside instrument may be isolated electrically from the case. In this way the common point where the bridge and shields are grounded is at the coaxial connector which is in the foreground in Plate VI. Notice that the outer metal case provides further shielding and is grounded at a single point by the terminal shown between the coaxial connector and the oscillator input.

The primary and secondary of the input transformer are externally shielded from each other by a partition below the transformer as shown in Plate VII. The electrostatic shielding between the windings is grounded to the chassis at the transformer case.

The Detector

The detector makes use of an "Electron Ray" tube which contains a triode and indicator tube in the same envelope. The tube construction is similar to that of an ordinary tube except the grid and plate only surround the bottom portion of the cathode, which extends into the indicator part of the tube.

Immediately over the top of the cathode is a circular fluorescent

EXPLANATION OF PLATE V

The bridge and detector shown with the outer case removed

PLATE V

EXPLANATION OF PLATE VI

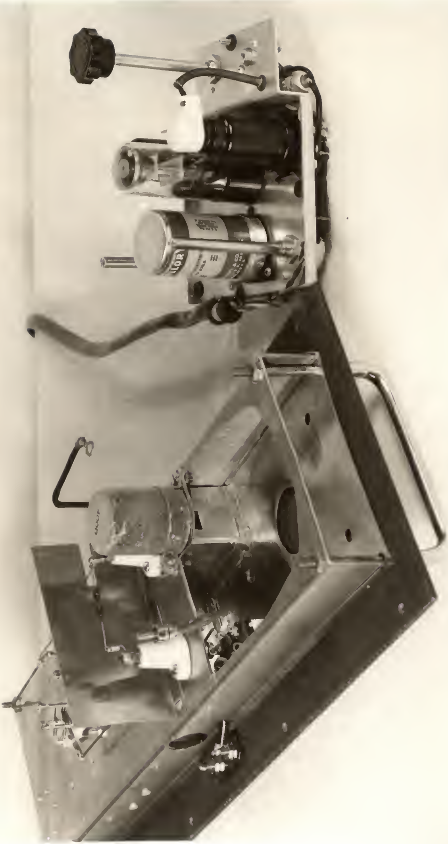
The bridge and detector disassembled showing the common grounding point at the coaxial cable connection and the parts layout

PLATE VI

EXPLANATION OF PLATE VII

The bridge and detector disassembled
to show the electrostatic shielding

PLATE VII



disc surrounded by a short cylindrical anode. Normally the electrons attracted from the cathode by the positive potential on this anode would hit the fluorescent screen on their way to the anode and cause it to glow. There is, however, a small thin rod which extends from the plate of the triode, upward between the cathode and the target of the indicator portion of the tube. When this rod is maintained at a potential slightly lower than the target, it repels the electrons in the neighborhood of the rod so that a shadow appears on the target.

The 6E5 tube was developed for use as tuning indicators in radios in about 1935. In 1936 Breazale (2) made use of the tube as an A-C bridge detector. Most of the detector circuits used since then seem to have evolved from Breazale's original circuit.

The characteristics of the 6E5 tube are reproduced on Plate VIII and were taken from Spangenberg (23). Inspection shows that as the grid to cathode voltage varies from zero to approximately minus 7.5 volts, the shadow angle goes from 90 to 0 degrees respectively. The cathode current varies very little over this range. This permits the use of a variable cathode bias resistor so the tube shadow angle may be adjusted to close when there is no signal on the grid. Then a positive signal applied to the grid will cause the shadow angle to "open" and a negative signal will do nothing since the tube is already biased to approximately cutoff. Thus the tube also functions as a half wave rectifier. A one tenth microfarad capacitor was added across the plate load resistor so power hum would not show up as fuzziness of the shadow, and to smooth the rectified signal so a sharper shadow could be obtained.

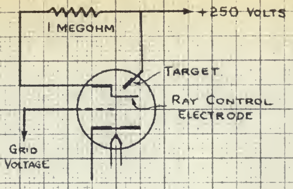
Two stages of amplification were used to obtain the necessary sensitivity. The first stage consists of a 6J7 Pentode which was chosen

EXPLANATION OF PLATE VIII

Characteristic curves of the

6E5 Electron Beam Tube

PLATE VIII


+250 Volts
1 Megohm
Target
Ray Control
Electrode
Grid
Voltage

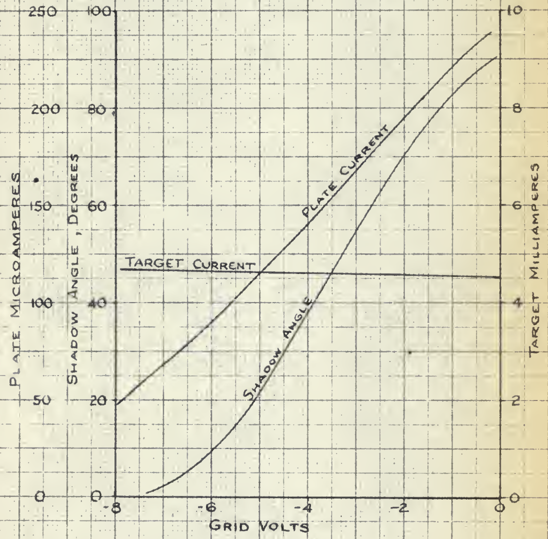


Plate Microamperes
250
200
150
100
50
0
Shadow Angle, Degrees
100
80
60
40
20
0
Target Milliamperes
10
8
6
4
2
0
Plate Current
Target Current
Shadow Angle
-8
-6
-4
-2
0
Grid Volts

because it has a high gain and the grid connection is on the top well isolated from the filament pins below. The second stage is a 6SJ7 Pentode which was also chosen for its high gain. The circuit values were obtained from the tube applications charts in the RCA Receiving Tube Manual (17). The gain was controlled by using one megohm potentiometers on the inputs of each tube which were connected to the same shaft. If a lower gain is desired, both stage gains will be decreased so the inherent noise within the first stage will not be amplified in greater proportion to the signal.

The coupling capacitor between the stages was chosen so the response at 60 cps was low compared to the response at 1000 cps.

The detector construction is shown in Plates V, VI, and VII. All wiring on the detector was point to point to minimize the possibility of hum pickup and instability. The circuit was laid out so the first stage would be as close as possible to the toggle switch on the bridge which selects either the internal or external detector. The power supply was decoupled between each stage with a 20 microfarad capacitor and all filament wiring was run on the top side of the chassis to provide shielding of the circuit from 60 cps pickup.

The detector was mounted by rubber grommets as shown in Plate V, and was grounded by a single wire to the common grounding point at the coaxial connector.

The plate voltage to the 6E5 may be adjusted by the potentiometer shown at the upper left side of the indicator tube and the bias adjustment is the lower left potentiometer (Plate VI). These may both be reached from the front of the instrument with a screwdriver.

The sensitivity of the detector to 1000 cps and 60 cps signals was checked at various plate voltages by varying the voltage input with a General Radio Type 654-A voltage divider. The input to the divider was set at .05 volts R.M.S. by measurement with a Tektronix calibrated oscilloscope. The angle of shadow was measured with an overlaying templet marked in degrees. Plate IX shows graphs of the sensitivity curves. The data is tabulated in the appendix under Tables 6 and 7. The greatest sensitivity occurs at the minimum potentiometer setting of 165 volts but the tube is rather dim at this voltage. A setting of about 200 volts seemed to provide the optimum characteristics.

The minimum easily detected voltage input was about 20 microvolts which makes the sensitivity much greater than actually needed for this application. It was used as the detector for most of the Freon dielectric investigation work both on this bridge and a General Radio type 716A bridge. The sensitivity was never turned to the maximum position.

The schematic of the detector appears as Plate XVI in the Appendix.

The Power Supply

The power supply is shown in Plate III and the schematic is Plate XVII in the Appendix. It is of conventional design, the component values being fairly standard for this size power supply. It is rated at 40 milliamps and drops from about 295 at no load to about 260 at full load. Filament voltage is available at 6.3 volts and 2 amperes. A relay is included in the power supply so accessories may be plugged into the outlet provided in the chassis and turned on and off from a light duty switch connected through the power cable.

EXPLANATION OF PLATE IX

Sensitivity curves of the detector

with the following conditions:

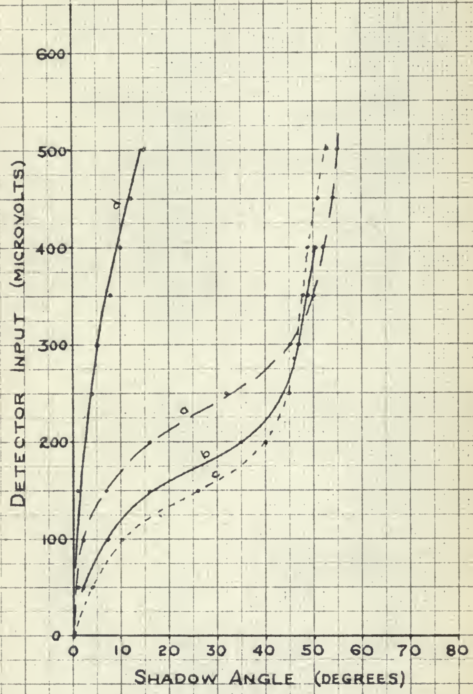
(a) Response to a 1000 cps signal with an indicator tube plate voltage of 280 volts

(b) Response to 1000 cps with plate voltage of 200 volts

(c) Response to 1000 cps with plate voltage of 165 volts

(d) Response to 60 cps with plate voltage of 200 volts

PLATE IX


DETECTOR INPUT (MICROVOLTS)
600
500
400
300
200
100
0
a
b
c
d
0
10
20
30
40
50
60
70
80
SHADOW ANGLE (DEGREES)

CALIBRATION OF THE ELEMENT AND BRIDGE

A photograph of the calibration setup is shown in Plate X. The element was supported by two adjustable stands which allow it to be carefully leveled. On one end was attached a sight glass and slide projector lens. The lens could also be leveled so the liquid surface would be parallel to the axis of the lens holder. A quarter inch copper line was run from the low point of the sight glass to the bottom of the storage tank, and another line was run from the high point of the sight glass to the top of the tank. Thus the liquid could be raised within the element by turning the handwheel which raises the storage tank. Shutoff valves and a charging valve were provided in both lines so the element could be disconnected without recharging the tank side of the circuit.

Calibration measurements of capacity were taken with a General Radio Type 716A capacitance bridge and a Dumont Oscilloscope was used as the null detector until the instrument null detector was constructed.

Before charging, the parts of the system were washed several times with carbon tetrachloride and dried by applying heat while circulating dry air through them. Each part was then blown out with Freon-12. After assembling, a vacuum was drawn on the system and the tank and element were charged with liquid Freon-12 to about half full.

The element and lens were then carefully leveled with a Lufkin precision machinists level. The point of the sight glass coinciding with the center of the element had previously been determined by measurement on a layout block. The lenses and screen were adjusted to magnify the image ten times.

EXPLANATION OF PLATE X

Picture showing the calibration setup

(1) Oscillator

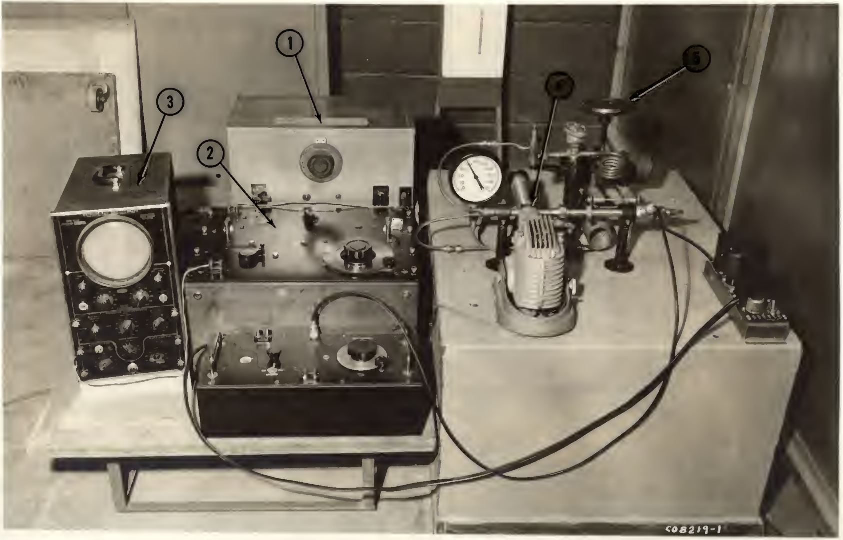
(2) General Radio Corporation 716-A Capacitance bridge

(3) Oscilloscope for use as a Null Detector

(4) Lense and sight glass for projecting an image of the liquid

(5) Hand wheel to raise the liquid level by raising the tank

PLATE X



A six inch rule, marked in sixty fourths of an inch, was positioned on the screen to give an indication of level, one inch on the rule being equivalent to a change in level of one tenth of an inch. The level could then be read to within one and one half thousandths of an inch.

Since partial decomposition of chlorinated compounds may occur when exposed to light, a masonite shutter was used between the slide projector light and the sight glass so that light passed through the glass only when a measurement was being taken. Plate XI shows a typical projected image through the sight glass.

Data for the capacitance of the element at different levels were taken at 65 psig and are tabulated in Table 1 in the Appendix. The values of capacity versus level at 180 psig were found by wrapping the element and sight glass with a type LU20 sheathed heating element made by Rockbestos Products, Inc.

The element was then filled completely with liquid, except for the gas in the upper loop, and the valves to the storage tank were closed. The entire element and sight glass were then heated slowly, by controlling the heater voltage manually, until a pressure of 180 psig was reached and had stabilized for several minutes. Capacitance and level readings were then taken and the upper valve was cracked slightly to release some of the Freon to the storage side of the system. After again stabilizing at 180 psig readings were taken, and the process continued until the element was empty. This procedure was followed twice with good repeatability of the data. The data for 180 psig are contained in Table 2 in the Appendix.

Data were taken for various pressures to obtain calibration curves between the two extremes of pressure. These data were obtained by

EXPLANATION OF PLATE XI

Picture showing the projected image
of the liquid on the screen
This gives a magnification of 10

PLATE XI

setting the liquid to approximately the level desired, closing the valves and heating slowly, letting the pressure stabilize at the various pressures desired. Readings were taken at each point, and the process repeated as the element was cooled slowly to check the values.

This procedure was repeated until sufficient data were obtained to plot the curves for 100, 120, and 160 psig. These data are contained in Table 3 of the Appendix and the plotted calibration curves are shown in Plate XII.

All capacitance values are with respect to the change in capacity from the condition in which the element contains air. Thus when setting up the instrument the zero point on the bridge may be set when the element is evacuated or when it contains air.

The conversion from Level to per cent Liquid was accomplished by the use of Table 8 and Plate XIX.

The bridge was calibrated by first calibrating a General Radio 755A variable capacitor with the General Radio 716-A bridge and then connecting this to the bridge. The dial was calibrated in .5 mmf increments.

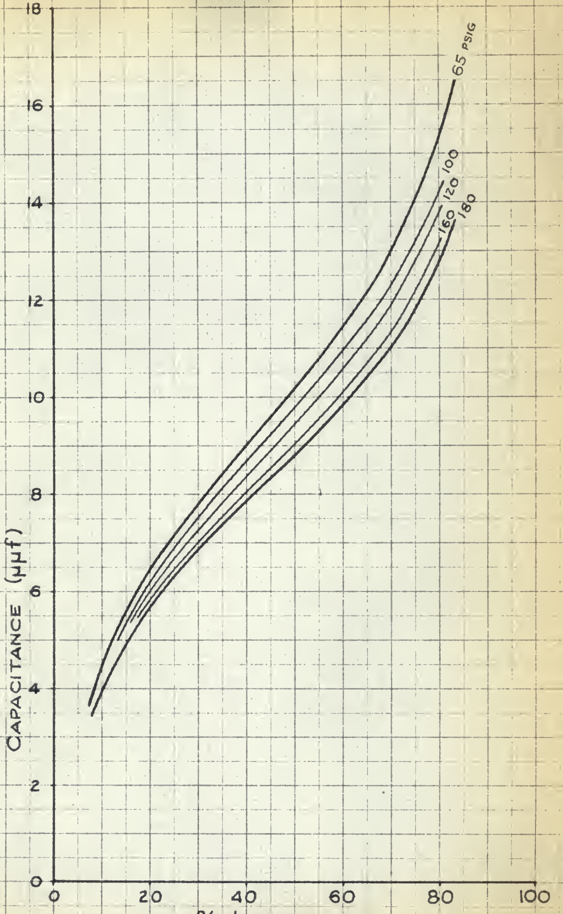
The bridge was corrected for an average power factor of 0.3 per cent by the addition of two precision resistors totaling 2810 ohms in series with the balancing capacitors. This power factor is low enough that no correction would have been essential, but the bridge is slightly easier to balance with the resistors. One advantage of this type null indicator is that should there be a difference in power factor which makes complete balance impossible, the bias may be adjusted so the shadow closes when the bridge is the closest to balance. With proper handling of the controls this balance may be just as sharply displayed with a residual signal, as for a perfect bridge balance. More is said about this adjust-

EXPLANATION OF PLATE XII

Calibration curves for percent liquid in the tube cross section vs. capacitance at saturation pressures of 65, 100, 120, 160, and 180 psig.

Data for the curves is contained in tables 1, 2, and 3 in the appendix

PLATE XII


CAPACITANCE (μμf)
% LIQUID
65 PSIG
100
120
160
180
0
2
4
6
8
10
12
14
16
18
0
20
40
60
80
100

ment in the operating instructions contained in the Appendix.

THE DIELECTRIC CONSTANT

Freon-12 has been known to be a very good high voltage insulator for many years, and several authors (2) (5) have thoroughly studied its dielectric breakdown properties. Fuoss (8) has done considerable research on the dielectric constants of the Fluorine Compounds including Freon-12, but his measurements only include the vapor state at pressures below atmospheric.

Beacham and Divers (1) have done research on the effect of impurities such as water and oil on the dielectric properties of Freon-12, Carrene-7, and Freon-22. Their main concern was with the insulation resistance and dielectric strength which effect the size and construction of sealed motor units.

During the course of their investigations they obtained a dielectric constant of Freon-12 in the pure liquid state of 1.78. The temperature was not stated, but their other measurements were at 72° F. so this is evidently the temperature at which this value was measured. After adding water to saturate the refrigerant at 72° F, they obtained a dielectric constant of 1.90. Addition of 1% by volume of non-inhibited naphthenic refrigeration oil, gave a dielectric constant of 1.77, and addition of both oil and water gave a dielectric constant of 1.90.

Eiseman (7) has made a study on the influence of the Freon refrigerants on the electrical performance of the hermetic refrigeration system. During the course of measuring resistances in a test cell he also measured capacitance and calculated the dielectric constant of liquid freon at 77° F. as 2.1, with an estimated accuracy of ± 10 to

15 per cent.

Since there seemed to be little or no information on the dielectric properties of either the liquid or vapor state at higher pressures, the writer decided to use the capacitance element as a test cell in the hopes that information might be gained for use in future designs.

EXPERIMENTAL PROCEDURE AND RESULTS

The test cell capacity was first determined by filling the element with Benzene which has a dielectric constant of 2.276 @ 77° F and determining the total capacity of the element and cable. The capacity was then checked with air as the dielectric (D = 1.000) and the test cell capacity determined as follows.

The total capacity = stray capac. + the capacity of the test cell

The stray capacity consists of the cable, connector, etc. while the test cell is only that portion of the element whose capacitance is affected by the dielectric.

The total capacity with Benzene dielectric is equal to

$$163.4 \text{ mmf} = C_s + 2.276\, C_e \qquad \begin{array}{l} C_s = \text{stray cap.} \\ C_e = \text{element capac. in air} \end{array}$$

The total capacity with air dielectric is equal to

$$142.3 \text{ mmf} = C_s + 1.000\, C_e$$

Solving these gives $C_s = 125.7$ mmf

$C_e = 16.6$ mmf

The setup for calibrating the instrument was then used to determine the dielectric properties.

For the determination of liquid state characteristics the element was sloped downward so it would always be completely full of liquid. It

was then filled with liquid Freon-12 from the storage tank and the valves were closed. The element was then well insulated and heat was supplied by the element to the sight glass so no gas would be formed within the element to cause gas bubbles. The pressure rise from 68 to 180 psig occurred over a period of about 5 hours so that temperature equilibrium could be fairly well assured. Capacitance readings were taken every two to five psi. The element was then cooled at about the same rate by gradually removing the heat at the sight glass and recording the capacitances.

The dielectric constant was calculated by the following equation.

$$C_m = C_s + D\,C_e$$

D = Dielectric Const.
C_m = Measured capacity
C_s = Stray cap.(125.7 mmf)
C_e = Element cap.(16.6 mmf)

The calculated dielectric constants for the liquid state versus the saturation pressure are tabulated in Table 4 in the Appendix. These values are shown in graphical form in Plate XIII. The zeros represent the values found as the temperature was increased and the crosses represent the values found as the temperature decreased.

The vapor state was tested by the same procedure except the element was slanted upward. Dielectric constants were determined by the same method. The calculated values appear in Table 5 of the Appendix. The graph of the dielectric constants appears as Plate XIV.

Precautions Taken

The system was disassembled and cleaned as before, then recharged with Freon-12 to see if the projector light had any effects as far as changing the dielectric properties of the Freon during the calibration

EXPLANATION OF PLATE XIII

The dielectric constant of saturated liquid Freon-12 versus the gauge pressure

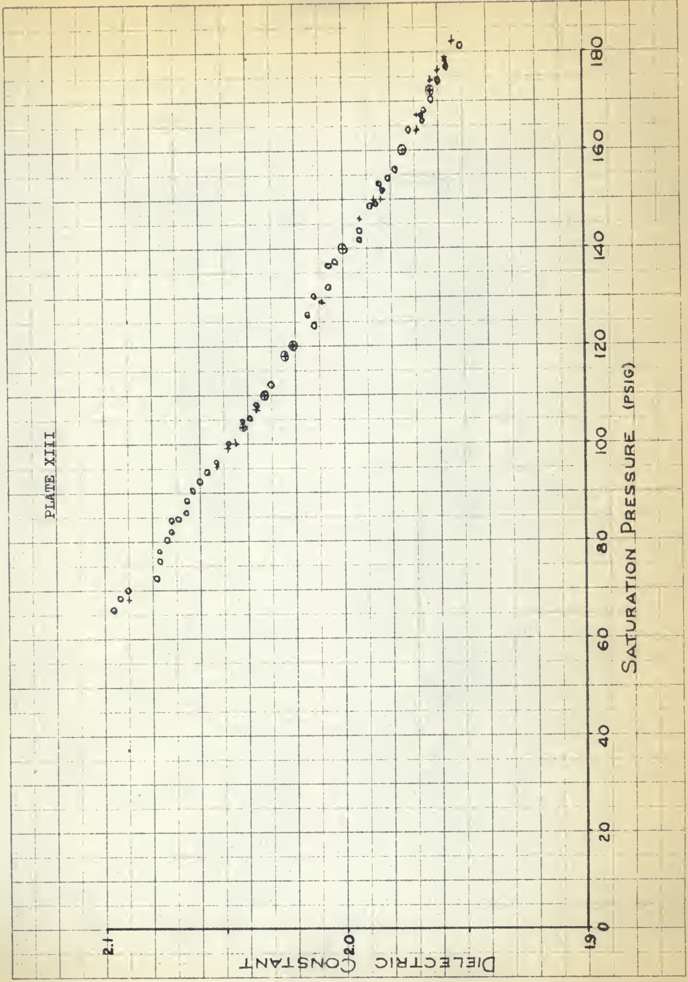


PLATE XIII
DIELECTRIC CONSTANT
2.1
2.0
1.9
SATURATION PRESSURE (PSIG)
0
20
40
60
80
100
120
140
160
180

EXPLANATION OF PLATE XIV

The dielectric constant of saturated Freon-12 vapor vs. the gauge pressure

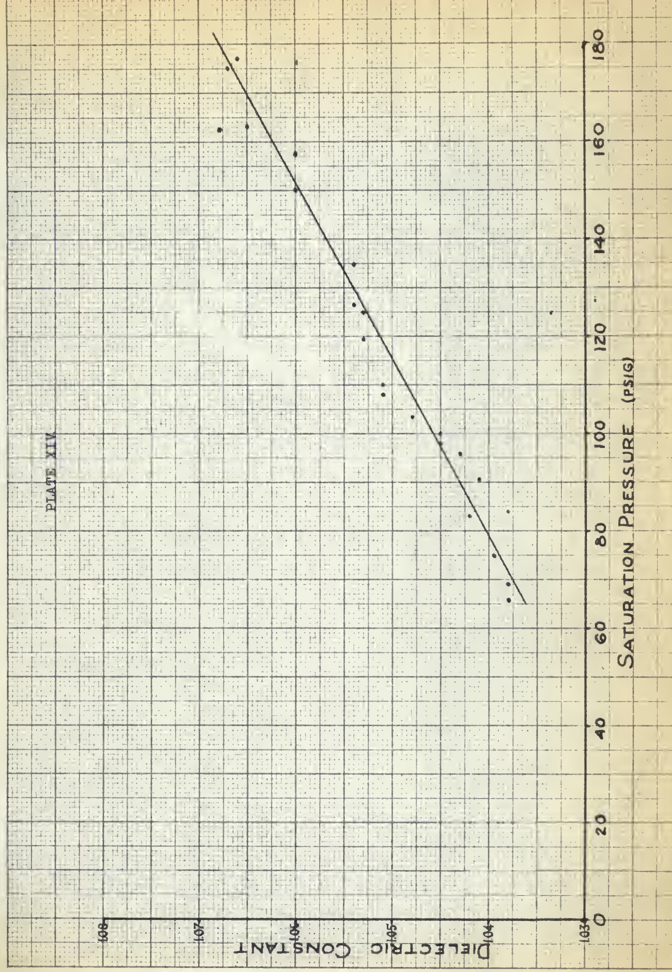


PLATE XIV
Dielectric Constant
1.03
1.04
1.05
1.06
1.07
1.08
Saturation Pressure (PSIG)
0
20
40
60
80
100
120
140
160
180

of the element. No effects were detectible within the accuracy of the measuring equipment.

The element was then checked for temperature sensitivity by connecting a standpipe to one end so it was vented to the atmosphere and submerging it in oil. The oil bath was then heated gradually to 130° F. while constantly stirring the oil. No change in the capacity of the element was noted on the 716A capacitance bridge.

CONCLUSIONS

The instrument (described above) can be used for the measurement of level of Freon-12 liquid in a horizontal tube, with an expected accuracy of 1% of full scale. Satisfactory performance was obtained for saturation pressures of 65 to 180 psig. Calibration curves for the various pressures are given in the report, together with a detailed description of the calibration procedure.

The values of the dielectric constant for the liquid phase of Freon-12 decrease from about 2.100 to 1.955 over the pressure range from 64 psig to 180 psig respectively. The value at 77° F. is about 2.08 which is within 1% of the value found by Eiseman (7).

The dielectric constant for the vapor state increases from 1.036 to 1.068 over the pressure range of 65 psig to 180 psig respectively. No other data was available with which to make a comparison.

ACKNOWLEDGMENTS

The author wishes to express his appreciation to Dr. R. G. Nevins, major instructor, for his help and advice on this project.

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APPENDIX

OPERATING INSTRUCTIONS

The Element

The element must be level in order to be accurate. The hexagon shaped sleeve on the body of the element has the same outside dimension as the housing around the electrical connector. A level may be laid directly across the element and the tube will be in alignment with the leveling points.

Mounting the Cable

The cable should be taped in one position or otherwise protected from strain or bending. Any damage or strain on the cable may change its capacity and make it necessary to reset the zero point of the bridge. This means either evacuating the system or removing the element.

Choice of an Oscillator

The oscillator may be any oscillator capable of generating a fairly good waveform 1000 cps signal. Unless it has a transformer output, the ground connection from the oscillator should be connected to the oscillator terminal marked G. The signal should not be over 2 volts R.M.S.

The Power Supply

The power supply may be used as a general purpose power supply and will furnish about 260 volts at 40 ma. and 6.3 v.a.c. @ 2 amperes.

Power may be taken either from the terminal strip or from the

octal socket. Two pins on the socket may be used to connect a remote power switch to the unit.

The fuse should be no larger than 1½ amperes.

The Detector

Either the internal detector or an external detector such as a high gain oscilloscope may be used to detect bridge balance. The detector switch is wired so it will automatically short the external binding posts when it is in the internal position and will short the internal detector input when it is in the external position.

The sensitivity of the detector may be varied by turning the knob located on the right side of the "Eye Tube" clockwise to increase sensitivity, and counter-clockwise to decrease sensitivity.

There are two holes on the front panel immediately to the right of the left handle. The hole nearest the back of the bridge covers a screwdriver adjustment for the plate voltage of the "Eye Tube." The hole nearest the front covers the screwdriver bias adjustment to close or open the shadow angle of the "Eye Tube."

To adjust the shadow angle to close when no signal is present, place the detector switch on the external position and adjust the bias until the shadow is just closed. When the bridge is balanced perfectly the "eye" will then be completely closed.

If perfect bridge balance cannot be obtained without turning the sensitivity control to almost the minimum, the balance may be adjusted as close as possible, then, with the sensitivity turned up slightly, the bias may be adjusted to just close the shadow. The residual voltage will be biased out and the change in voltage will be indicated.

With proper adjustment of the bias and the sensitivity control, the balance may be made as sensitive as it is when perfect balance is possible.

The above procedure should not be necessary with the Freon element unless a poor connection develops or there is a leakage path somewhere in the circuit or element.

The Bridge

The bridge dial is calibrated in micro microfarads. To adjust the bridge to correspond to the element calibration curves, the element must be either under a vacuum, or have air between its electrodes. The chrome button on the left side of the dial covers the screwdriver adjustment of the cable compensating capacitor. With the bridge connected for operation, set the dial to zero and obtain a null balance by adjusting the cable compensating capacitor with a small narrow screwdriver. The dial should then be used to obtain balance several times to make sure balance is obtained at exactly zero. The instrument may then be used with Freon. The capacity bridge reading is in micro microfarads and the liquid level conditions may be obtained from Plate XII.

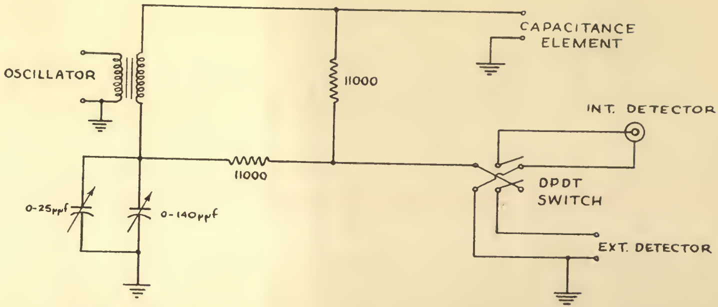
The bridge dial knob should <u>never</u> be taken off because the bridge has been calibrated in this one position and the variable capacitance is not linear with respect to the shaft angle.

The power supply is for <u>110 V. operation only</u>.

EXPLANATION OF PLATE XV

Schematic diagram of the bridge circuit

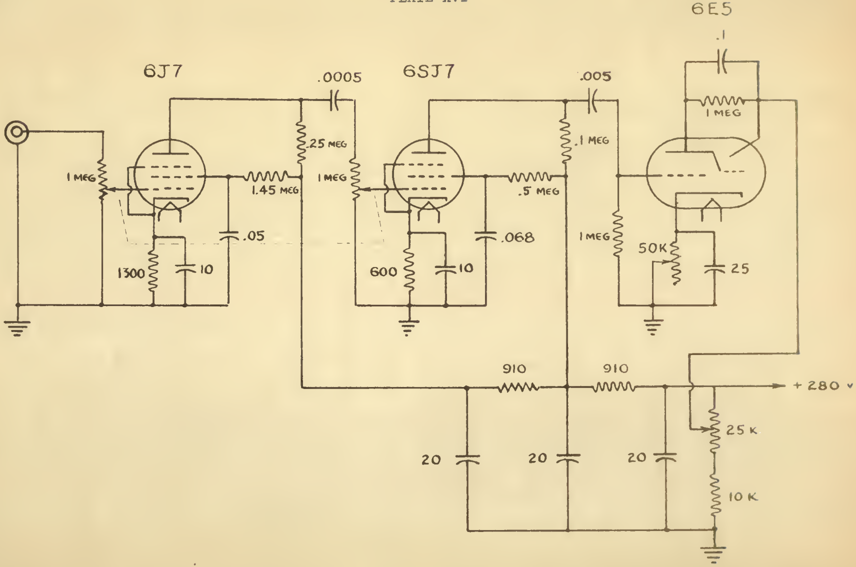
PLATE XV


CAPACITANCE ELEMENT
OSCILLATOR
11000
INT. DETECTOR
11000
DPDT SWITCH
0-25μμf
0-140μμf
EXT. DETECTOR

EXPLANATION OF PLATE XVI

Schematic diagram of the Null detector circuit

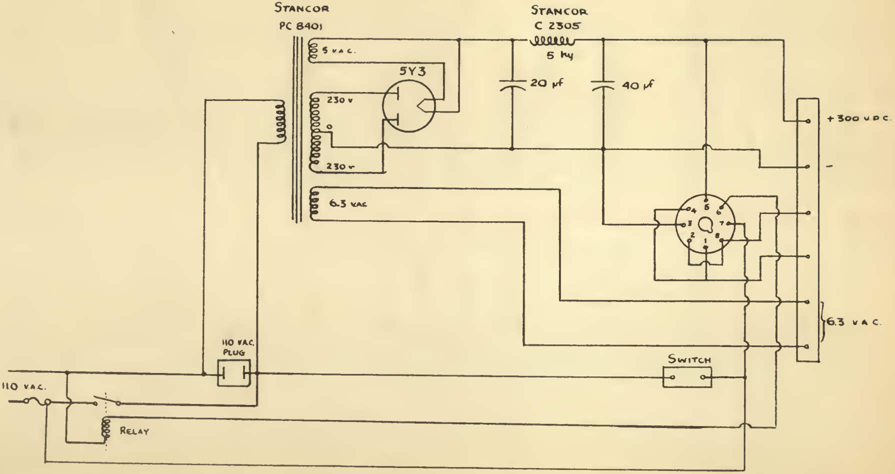
PLATE XVI


6J7
.0005
6SJ7
.005
6E5
.1
1 MEG
.25 MEG
1 MEG
1 MEG
.1 MEG
1.45 MEG
.5 MEG
.05
.068
1 MEG
50K
1300
10
600
10
25
910
910
+ 280 v
25 K
20
20
20
10 K

EXPLANATION OF PLATE XVII

Schematic diagram of the power supply

PLATE XVII



TERMINAL STRIP IS SHOWN FROM BOTTOM VIEW

Parts List for Null Detector and Power Supply

R_1	25 K 4 watt potentiometer
R_2	50 K potentiometer
R_3R_4	1 meg dual potentiometer
	1 meg type M pot. section
S_1	DPDT Toggle switch
$C_1C_2C_3$	20-20-20 450v. capacitor
C_4	20 mfd. - 25 UDC Elect. cap.
C_5C_6	10 mfd. - 25 UDC Elect. cap.
C_7	.005 mfd. 600v. capacitor
C_8	.0005 mfd. 600v. mica capacitor
C_9	.05 mfd. 400v. capacitor
C_{10}	.1 mfd. 200 VDC. capacitor
C_{11}	.068 mfd. capacitor
V_1	6SJ7 Vacuum tube
V_2	6J7 Vacuum tube
V_3	6E5 Electron Ray tube
R_5R_6	.51 meg. resistors
R_7	1300 resistor
R_8	.24 meg. resistor
R_9	560 resistor
R_{10}	1.5 meg. resistor
R_{11}	.1 meg. resistor
$R_{12}R_{13}R_{14}$	910 resistor
T_1	Power transformer-Stancor, type PC 8401
T_2	Filter Reactor-Stancor, type C 2305
V_4	5Y3 tube
$C_{12}C_{13}C_{14}$	20 mfd. 430 VDC Elect. Capacitor

EXPLANATION OF PLATE XVIII

Detailed drawing of the capacitance element

PLATE XVIII

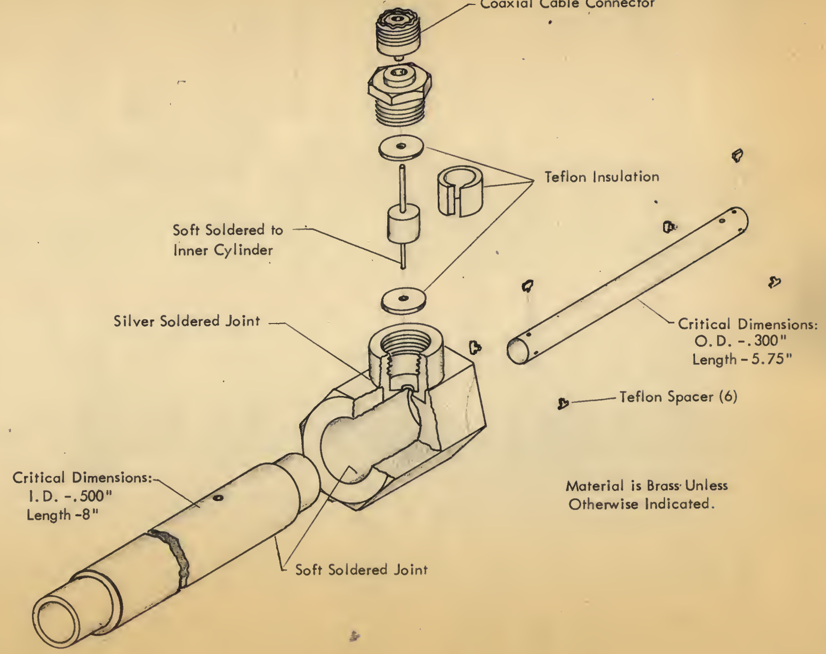

Coaxial Cable Connector
Teflon Insulation
Soft Soldered to Inner Cylinder
Silver Soldered Joint
Critical Dimensions: O.D. -.300" Length - 5.75"
Teflon Spacer (6)
Critical Dimensions: I.D. -.500" Length -8"
Soft Soldered Joint
Material is Brass Unless Otherwise Indicated.

Table 1. Calibration data for saturation pressure of 65 psig.

Total Capacity[1] (mmf)	Bridge Dial Capacity[2] (mmf)	Liquid Level (Inches)	% Liquid[3]
160.65	18.35	.425	90.5
160.6	18.3	.3875	83.0
158.65	16.35	.3875	83.0
157.75	15.45	.3750	80.4
157.05	14.75	.3625	77.5
156.45	14.15	.3500	74.7
155.9	13.6	.3375	71.5
155.05	12.75	.3250	68.8
154.65	12.35	.3125	65.6
154.0	11.7	.3000	62.6
153.8	11.5	.1875	60.0
153.4	11.1	.2750	56.3
152.95	10.65	.2625	53.5
152.50	10.20	.2500	50.0
152.2	9.9	.2375	47.0
151.8	9.5	.2250	43.7
151.4	9.1	.2125	40.2
151.0	8.7	.2000	37.3
150.6	8.3	.1875	34.0
150.2	7.9	.1750	31.1
149.8	7.5	.1625	28.1
149.5	7.2	.1500	25.3
149.00	6.7	.1360	22.1
148.7	6.4	.1250	19.5
148.25	5.95	.1125	17.2
147.8	5.5	.1000	14.5
147.3	5.0	.0875	12.0
146.72	4.42	.0750	9.4
146.09	3.79	.0625	7.5
143.6	1.3	.0500	5.3
143.35	1.05	.0375	3.5

[1]Total capacity includes element and cable.
[2]Bridge capacity = total capacity minus capacity with air dielectric.
[3]% Liquid = % of cross section containing liquid.

Table 2. Calibration data for saturation pressure of 180 psig.

Total Capacity (mmf)	Bridge Dial Capacity (mmf)	Liquid Level (Inches)	% Liquid
154.6	12.3	.3610	77.2
154.1	11.8	.3500	74.7
153.4	11.1	.3293	70.0
152.7	10.4	.3079	65.0
151.5	9.2	.2672	54.8
150.72	8.42	.2313	45.1
149.8	7.5	.1938	35.7
148.6	6.3	.1469	24.6
146.9	4.6	.0922	13.0
146.3	4.0	.0734	9.3
145.7	3.4	.0641	7.8
156.0	13.7	.3906	83.7

Table 3. Calibrations for varied saturation pressures.

Pressure (psig)	Total Capacity (mmf)	Bridge Dial Capacity (mmf)	Liquid Level (Inches)	% Liquid
80	151.15	8.85	.2125	40.3
90	151.05	8.75	.2125	40.3
100	151.0	8.7	.2125	40.3
110	150.9	8.6	.2140	40.5
120	150.85	8.55	.2140	40.5
130	150.8	8.5	.2156	41.0
140	150.72	8.42	.2170	41.2
150	150.6	8.3	.2188	41.7
160	150.55	8.25	.2190	42.0
180	150.4	8.1	.2203	43.0
100	155.45	13.15	.3516	75.0
120	155.15	12.85	.3516	75.0
140	154.9	12.6	.3532	75.2
160	154.6	12.3	.3532	75.2
180	154.3	12.0	.3547	75.5
80	153.8	11.5	.2953	62.0
100	153.5	11.2	.2969	62.0
120	153.26	10.96	.2969	62.0
160	152.75	10.45	.3000	62.6
120	149.4	7.1	.1625	28.1

Table 4. Data for Calculation of dielectric constant.

Saturation Pressure (psig)	Measured Capacity (mmf)	Internal Element Capacity (mmf)	Dielectric Constant
68	160.4	34.7	2.090
95.5	159.8	34.1	2.053
96.	159.8	34.1	2.053
99.5	159.7	34.0	2.048
100	159.66	33.96	2.045
103.5	159.6	33.9	2.042
103.5	159.6	33.9	2.042
107	159.5	33.8	2.036
110	159.45	33.75	2.033
118	159.3	33.6	2.024
120	159.25	33.55	2.021
129	159.05	33.35	2.009
140	158.9	33.2	2.000
146.5	158.8	33.1	1.993
149.5	158.7	33.0	1.987
150.0	158.65	32.95	1.984
160.0	158.5	32.8	1.975
164.0	158.4	32.7	1.969
167.0	158.4	32.7	1.969
172	158.3	32.6	1.963
174.0	158.3	32.6	1.963
176	158.25	32.55	1.960
179	158.2	32.5	1.957
182	158.15	32.45	1.954
181	158.1	32.4	1.951
178.5	158.2	32.5	1.957
177	158.2	32.5	1.957
174	158.25	32.55	1.960
172	158.3	32.6	1.963
170	158.3	32.6	1.963
168	158.35	32.65	1.966
167	158.4	32.7	1.967
166	158.4	32.7	1.967
164	158.45	32.75	1.972
160	158.5	32.8	1.975
156	158.55	32.85	1.978
169	158.6	32.9	1.981
152.5	158.65	32.95	1.984
152	158.65	32.95	1.984
149.0	158.7	33.0	1.987
148.0	158.75	33.05	1.990
143.0	158.85	33.15	1.993
141.0	158.85	33.15	1.993
140	158.9	33.2	2.000
137	158.95	33.25	2.003
136	159.0	33.3	2.006
132	159.0	33.3	2.006
130	159.1	33.4	2.012
126	159.15	33.45	2.015

Table 4 (Cont.)

Saturation Pressure (psig)	Measured Capacity (mmf)	Internal Element Capacity (mmf)	Dielectric Constant
124	159.2	33.5	2.012
120	159.25	33.55	2.021
118	159.3	33.6	2.024
117.5	159.3	33.6	2.024
112.0	159.4	33.7	2.030
110.0	159.45	33.75	2.033
108.0	159.5	33.8	2.036
105.0	159.55	33.85	2.039
104.0	159.6	33.9	2.042
103.0	159.6	33.9	2.042
100.0	159.7	34.0	2.048
96.0	159.8	34.1	2.053
94.0	159.83	34.13	2.056
92.0	159.9	34.2	2.060
90.0	159.95	34.25	2.063
88.0	160.0	34.3	2.066
86.0	160.01	34.31	2.066
84.5	160.05	34.35	2.069
84.0	160.1	34.4	2.072
82.0	160.1	34.4	2.072
80.0	160.15	34.45	2.075
78.0	160.2	34.5	2.077
76.0	160.2	34.5	2.077
72.0	160.3	34.6	2.078
70.0	160.4	34.7	2.090
68.0	160.45	34.75	2.093
66.0	160.5	34.8	2.096

Table 5. Data for calculation of dielectric constant of freon vapor.

Saturation Pressure (psig)	Measured Capacity (mmf)	Internal Element Capacity (mmf)	Dielectric Constant
66	142.9	17.2	1.036
69	142.9	17.2	1.036
75	142.95	17.25	1.039
83	143.00	17.30	1.042
84	142.9	17.2	1.036
90.5	142.99	17.29	1.041
96	143.03	17.33	1.043
98	143.05	17.35	1.045
100	143.06	17.36	1.045
103.5	143.1	17.4	1.048
108	143.15	17.45	1.051
110	143.15	17.45	1.051
119.5	143.19	17.49	1.053
125.0	143.19	17.49	1.053
126.5	143.2	17.5	1.054
150	143.3	17.6	1.060
157	143.3	17.6	1.060
163	143.39	17.69	1.065
175	143.42	17.72	1.067
177	143.4	17.7	1.066
135	143.2	17.5	1.054

Table 6. Measured response of null detector with 1000 cps input.

Oscillator Voltage (RMS)	Voltage Divider Ratio	Detector Input (Microvolts)	Shadow Angle with Plate Voltage of		
			280	200	165
.05	.001	50	1	2	4
.05	.002	100	2	7	10
.05	.003	150	7	16	26
.05	.004	200	16	35	40
.05	.005	250	32	45	42
.05	.006	300	45	47	47
.05	.007	350	50	49	48
.05	.008	400	52	50	49
.05	.009	450	54	51	51
.05	.010	500	55	55	53
.05	.020	1,000	65	67	66
.05	.030	1,500	74	75	77
.05	.040	2,000	80	80	80
.05	.200	10,000	86	90	90

Table 7. Measured response of null detector with 60 cps input.

Oscillator Voltage (RMS)	Voltage Divider Ratio	Detector Input (Microvolts)	Shadow Angle with Plate Voltage of
			200
.05	.003	150	1
.05	.005	250	4
.05	.006	300	5
.05	.007	350	8
.05	.008	400	10
.05	.009	450	12
.05	.010	500	15
.05	.020	1,000	41
.05	.03	1,500	46
.05	.04	2,000	49
.05	.05	2,500	51
.05	.06	3,000	52
.05	.07	3,500	55
.05	.08	4,000	60
.05	.09	4,500	65
.05	.1	5,000	67
.05	.2	10,000	75

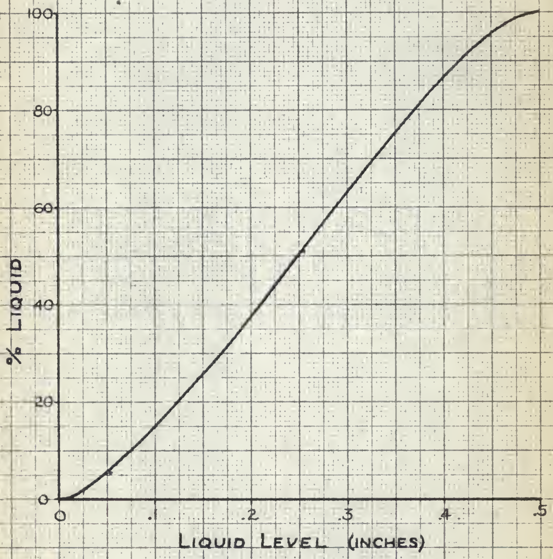
Table 8. Calculated data for % area vs. height of liquid for ½ inch diameter cross section.

Height	Area	% Area
.025	.0038	1.93
.050	.104	5.29
.075	.184	9.36
.100	.0286	14.55
.125	.0383	19.50
.150	.0494	25.30
.175	.0612	31.15
.200	.0734	37.35
.225	.0858	43.70
.250	.0987	50.00
.275	.1106	56.30
.300	.1230	62.60
.325	.1351	68.8
.350	.1469	74.7
.375	.1580	80.4
.400	.1677	85.3
.425	.1779	90.5
.450	.1860	94.6
.475	.1925	98.0
.500	.1963	100.0

EXPLANATION OF PLATE XIX

Percent of cross sectional area occupied by the liquid versus the height of the liquid for a ½ inch diameter cross section

PLATE XIX



A DESIGN OF A CAPACITANCE TYPE INSTRUMENT FOR THE DETECTION OF THE LEVEL OF CONDENSED FREON-12 IN A HORIZONTAL LINE

by

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B. S., Kansas State College
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The design of an electrical capacitance type liquid level instrument was initiated because an accurate method of measuring the level of condensed Freon-12 entering and leaving a horizontal tube was required in a research project at Kansas State College.

The author presents an instrument design consisting of a capacitance element, a wheatstone bridge circuit, and an electronic A-C bridge null detector.

The instrument can be used for the measurement of level of Freon-12 liquid in a horizontal tube, with an expected accuracy of 1% of full scale. Satisfactory performance was obtained for saturation pressures of 65 to 180 psig. Calibration curves for the various pressures are given in the report, together with a detailed description of the calibration procedure.

By using the same test setup, the author checked the dielectric constant for the liquid phase of Freon-12 at various saturation pressures, and for the vapor phase in the same range of pressures.

The values for the dielectric constant of the liquid phase decreased from 2.100 to 1.955 over the pressure range of 64 to 180 psig.

The vapor dielectric constant increased from 1.036 to 1.068 over the pressure range of 65 to 180 psig.